

New measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio

version 2

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Three candidate events for the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ have been observed in the pion momentum region below the $K^+ \rightarrow \pi^+ \pi^0$ peak, $140 < P_\pi < 199$ MeV/c, with an estimated background of $0.927 \pm 0.168^{+0.320}_{-0.237}$ events. Combining these observations with previously reported results yields a branching fraction of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ consistent with the standard model prediction.

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The rate of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays is among a handful of hadronic processes that can be accurately predicted in the standard model owing to knowledge of the transition matrix element from similar processes and minimal long-distance effects [1, 2]. The small branching ratio, $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$ [3], and the fact that this decay is a flavor-changing neutral current process makes it a sensitive probe of new physics effects [1]. Previous studies of this decay by experiment E787 at Brookhaven National Laboratory and its extension E949 have measured $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ based on the observation of three candidates with a total background of 0.44 ± 0.05 events in the pion momentum region $211 < P_\pi < 229$ MeV/c above the $K^+ \rightarrow \pi^+ \pi^0$ ($K_{\pi 2}$) peak (pnn1) [4, 5]. E787 set a consistent limit of $< 22 \times 10^{-10}$ at 90% C.L. based on one candidate with a total background of 1.22 ± 0.24 events in the momen-

tum region $140 < P_\pi < 195$ MeV/c below the $K_{\pi 2}$ peak (pnn2) [6, 7].

In this Letter we report the results of a search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ below the $K_{\pi 2}$ peak using 1.7×10^{12} stopped K^+ decays obtained with E949 as well as the final results on $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ from E949 data combined with E787 data.

The E949 apparatus and analysis of the data in the pnn1 region has been described elsewhere [5]. In this Letter, we concentrate on the apparatus and analysis features most relevant for pnn2. Identification of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays relies on detection of an incoming kaon, its decay at rest, and an outgoing pion with no other detector activity. A 710 MeV/c K^+ beam, produced by 21.5 GeV proton interactions on a platinum target, passed through two electromagnetostatic separators during transport to the E949 scintillating fiber tar-

get (TG). Typically 1.6×10^6 K^+ /s entered the E949 TG during a 2.2 s spill with a K^+/π^+ ratio of ~ 3 .

Incoming kaons were identified by a Cerenkov counter and two proportional wire chambers before being slowed by an 11.1 cm thick BeO degrader and an active degrader (AD), passing through a beam hodoscope and stopping in the TG. The AD comprised 39 2.2 mm thick copper disks interleaved with 40 layers of 2.2 mm plastic scintillator divided into 12 azimuthal segments. Scintillation light from each segment was transported via wavelength shifting fibers to a photomultiplier tube (PMT) that was read out by time-to-digital convertors (TDCs), GaAs CCD waveform digitizers (CCDs) sampling at 500 MHz [8] and analog-to-digital convertors (ADCs). The AD was capable of providing measurements of the incoming beam particle and activity coincident with K^+ decay in the TG. The TG consisted of 413 5 mm square and 3.1 m long scintillating fibers packed into a 12 cm diameter cylinder. Each 5 mm fiber was connected to a PMT and read out by TDCs, CCDs and ADCs in order to measure activity in the TG coincident with both the incoming kaon and the outgoing pion.

The momentum, trajectory and position of the outgoing π^+ were measured in a drift chamber [9]. The outgoing pion was slowed to a stop in a range stack (RS) of 19 layers of plastic scintillator with 24 segments in azimuth. PMTs on each end of the scintillator were read out by ADCs, TDCs and 500-MHz transient digitizers (TDs) [10] and enabled measurement of the pion range (R_π) and kinetic energy (E_π) as well as the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay sequence.

The barrel veto (BV) calorimeters of 16.6 radiation lengths (r.l.) at normal incidence provided photon detection over $2/3$ of 4π sr solid angle. Photon detection over the remaining $1/3$ of 4π sr solid angle was provided by a variety of calorimeters in the region from 10° to 45° of the beam axis with a total thickness from 7 to 15 r.l. [5]. Unlike the pnn1 analysis, this analysis also used the photon detection capabilities of the AD (6.1 r.l.) and the target (7.3 r.l.) that occupied the region within 10° of the beam axis.

This analysis was able to increase the signal acceptance by 40% and maintain the same background rate per stopped K^+ as the previous analysis [7] thanks to improved background rejection due to the upgrades of the AD and BV for E949. In addition the improved knowledge of the background contributions allowed the signal region to be divided into nine sub-regions (“cells”) with relative signal-to-background levels differing by a factor of ≈ 4 that were used in the likelihood method [11] to determine $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$.

We employed a “blind” analysis technique in which the signal region was not examined until all selection criteria (“cuts”) for signal had been established, the estimate of all backgrounds completed and acceptance of all cells determined. Two uncorrelated cuts with significant rejection

were developed for most backgrounds. After application of basic event quality cuts, inversion of one of the pair of cuts could then be used to select a background-enriched data sample containing N events. Inversion of the complementary cut selected a data sample on which the rejection \mathcal{R} of the first cut could be measured. The background was estimated as $N/(\mathcal{R} - 1)$. We ensured unbiased background estimates by dividing the data into one-third and two-third samples selected uniformly from the entire data set. Selection criteria were determined with the one-third sample and background levels were estimated from the two-third sample. In contrast to the analysis of the pnn1 region, some backgrounds do not have sufficiently distinct characteristics to permit isolation by cut inversion of a pure background sample and permit a measurement of \mathcal{R} with the data. For these backgrounds, \mathcal{R} was estimated with simulated data as described below.

Table I summarizes the estimated background levels. The largest background was due to $K_{\pi 2}$ decays in which the π^+ scatters in the TG, losing energy and obscuring the directional correlation with the photons from the π^0 decay that would otherwise be detected in the BV. Two cuts that suppressed this background were 1) identification of π^+ scattering and 2) detection of the photons from π^0 decay. The latter photon veto (PV) ability was improved in E949 with respect to E787 primarily due to the AD and augmentation of the BV by 2.3 r.l. Pion scattering was identified by kinks in the pattern of TG fibers attributed to the pion, by tracks that did not point back to the fiber containing the K^+ decay, by energy deposits inconsistent with an outgoing pion or by unexpected energy deposits at the time of the pion in fibers traversed by the kaon. The “CCDPUL” cut identified the latter signature by performing a least-squares fit to the CCD samples to identify the pulses due to activity coincident with the kaon and pion. The uncertainty in the $K_{\pi 2}$ TG-scatter background had comparable statistical and systematic contributions. The systematic uncertainty was determined by the range of PV rejection values measured on samples of $K_{\pi 2}$ scatter events selected by different scattering signatures in the TG or in different kinematic regions [12]. There was also a much smaller background from $K_{\pi 2}$ due to scattering in the RS that was similarly identified by the energy deposits and pattern of RS counters attributed to the track.

Additional backgrounds included $K^+ \rightarrow \pi^+ \pi^0 \gamma$ ($K_{\pi 2 \gamma}$), $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ (K_{e4}), $K^+ \rightarrow \mu^+ \nu(\gamma)$ and $K^+ \rightarrow \pi^0 \mu^+ \nu$ (muon), scattered beam pions (beam) and $K_L^0 \rightarrow \pi^+ \ell^- \bar{\nu}$ where $\ell^+ = e^+$ or μ^+ resulting from K^+ charge-exchange (CEX) reactions. Simulated data were used to estimate the rejection \mathcal{R} of the cuts that suppress K_{e4} , $K_{\pi 2 \gamma}$ and CEX backgrounds. These backgrounds could not be distinguished from the larger $K_{\pi 2}$ -scatter background based solely on the π^+ track. The K_{e4} process forms a background when the π^- and e^+ interact

Bkgd comp.	Additional factor for rejection or acceptance loss					Background estimate for signal region
	KIN	TD	DC	PV	REC	
$K_{\pi 2}$ TG	1.63			2.75	✓	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS	1.63			2.75	✓	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2\gamma}$	1.20			2.75		$0.076 \pm 0.007 \pm 0.006$
K_{e4}	2.70			✓		$0.176 \pm 0.072^{+0.233}_{-0.124}$
CEX		6.7		✓		$0.013 \pm 0.013^{+0.010}_{-0.003}$
Muon		3.08			✓	0.011 ± 0.011
Beam			1.0	✓		0.001 ± 0.001
Total background						$0.927 \pm 0.168^{+0.320}_{-0.237}$
Acc.	0.812	0.812	0.911	0.522	NA	

TABLE I: Summary of the applicable cuts, additional factors for rejection or acceptance loss, and contribution to the signal region for each background component. The middle columns indicate the additional rejection for each component from the tightening of the kinematic (KIN), TD, delayed coincidence (DC), photon veto (PV) and reconstruction (REC) cuts. A ✓ indicates that the cut was inverted to determine the background. The bottom row gives the relative acceptance loss associated with tightening each cut to divide the signal region into nine cells. The acceptance of the signal region was $(1.366 \pm 0.016 \pm 0.052) \times 10^{-3}$.

in the TG without leaving a detectable trace. Positron interactions are well-modelled in our EGS4-based simulation [13] and we used the π^- energy deposition spectrum in scintillator measured previously in E787 [14] to model π^- absorption. We assessed the systematic uncertainty in the K_{e4} background by varying the threshold of cuts on the energy deposited in the target fibers at the time of the pion. The kinematics cuts (KIN) defining the entire signal region were $140 < P_\pi < 199$ MeV/c, $60 < E_\pi < 100.5$ MeV and $12 < R_\pi < 28$ cm. We defined a smaller region $165 < P_\pi < 197$ MeV/c, $72 < E_\pi < 100$ MeV and $17 < R_\pi < 28$ cm where the lower and upper limits were chosen to suppress the K_{e4} background that peaks near 160 MeV/c and the tail of the $K_{\pi 2}$ peak, respectively.

Measurement of the K^+ charge-exchange reaction was used as input to simulate CEX events [5]. The requirement on the delayed coincidence (DC) between the reconstructed kaon and pion candidates provided suppression of CEX background as the emitted π^+ was required to be within the fiducial region of the TG. The systematic uncertainty was assessed with the same methodology as the K_{e4} background.

The rejection of the $K_{\pi 2\gamma}$ background was calculated using a combination of simulated $K_{\pi 2}$ and $K_{\pi 2\gamma}$ events and $K_{\pi 2}$ data events. The additional PV rejection due to the radiative photon was calculated from the photon distribution in simulated events and the rejection power of single photons as a function of angle and energy evaluated with $K_{\pi 2}$ data [15].

The muon and beam backgrounds were estimated en-

Region	N_{exp}	N_{obs}	$\mathcal{P}(N_{\text{obs}}; N_{\text{exp}})$	Combined
CCD_1	$0.79 \pm 0.35^{+0.30}_{-0.37}$	0	0.452 (0.652)	NA
PV_1	$9.09 \pm 0.65^{+1.38}_{-1.15}$	3	0.020 (0.044)	0.051 (0.130)
PV_2	$32.4 \pm 1.9^{+12.2}_{-7.9}$	34	0.613 (0.973)	0.140 (0.390)

TABLE II: Comparison of the expected N_{exp} and observed N_{obs} number of background events in three regions CCD_1 , PV_1 and PV_2 near the signal region. The central value of N_{exp} is given along with the statistical and systematic uncertainties. $\mathcal{P}(N_{\text{obs}}; N_{\text{exp}})$ is the probability of observing N_{obs} events or fewer when N_{exp} events are expected. The rightmost column “Combined” gives the probability of the combined observation in that region and the region(s) of the preceding row(s). The numbers in parentheses are the probabilities re-evaluated when N_{exp} is reduced by the systematic uncertainty [12].

tirely from data and were very small. As previous analyses had shown the muon background to be small [6, 7], the TD-based cuts on $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ identification were loosened to gain acceptance.

The reliability of the background estimates was checked by loosening the PV and CCDPUL cuts to define three distinct regions just outside the signal region. Each of the two regions, PV_1 and CCD_1 , were immediately adjacent to the signal region while a third region PV_2 , adjacent to PV_1 , was defined by further loosening of the PV cut. The number of expected and observed events and the probability of the observation are given in Table II. The 5.1% probability for the regions nearest the signal region may have indicated that the background was over-estimated. Given the inability to cleanly isolate each background component by cut inversion, some contamination is possible and would generally inflate the background estimates. Re-evaluation of the probabilities at the lower limit of the systematic uncertainties [12] gave 13.0% for the two closest regions and demonstrated that the assigned systematic uncertainties were reasonable.

After completion of the background studies, the signal region was examined and three candidates were found. The energy vs range for these observed candidates is shown in Figure 1 along with the results of previous E787 [6, 7] and E949 [4, 5] analyses. From these three observed candidates, $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.89^{+9.26}_{-5.10}) \times 10^{-10}$ was calculated using the likelihood method [11] taking into account the uncertainties in the background and acceptance measurements. When combined with the results of previous E787 [6, 7] and E949 [4, 5] analyses, we measured $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ or $< 3.35 \times 10^{-10}$ at 90% CL. Assuming $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73 \times 10^{-10}$, the signal-to-background (S/B) ratios for the three candidates are 0.20, 0.42 and 0.48, which can be compared with the S/B = 0.20 for the previous pnn2 candidate [6] and with the S/B = 59, 8.2 and 1.1 for the pnn1 candidates [4]. As an indication of the improvements in the analysis, a candidate in the best (worst) cell would have had S/B=0.84

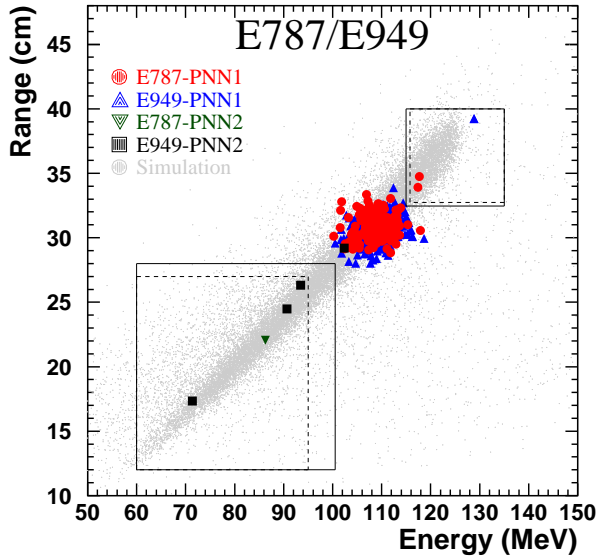


FIG. 1: The kinetic energy vs range of all candidate events passing all other cuts. The circles and upward-pointing triangles represent the events selected by the E787 and E949 pnn1 analyses, respectively. The downward-pointing triangles and squares represent the events selected by the E787 and E949 pnn2 analyses, respectively. The solid (dashed) lines represent the limits of the pnn1 and pnn2 signal regions for the E949 (E787) analyses. No kinematic cuts are applied to the simulated $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events (light gray).

(0.20). The probability that the three observed candidates were due to background only, given the estimated background in each cell, is 0.037. The probability that all $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates [4, 7] were due to background is 0.001. In summary, these observations imply a $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio consistent with standard model expectations.

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